

Strange decays from strange resonances

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Abstract

We discuss the mass spectrum and strong decays of baryon resonances belonging to the N , Δ , Σ , Λ , Ξ and Ω families in a collective string-like model for the nucleon. We find good overall agreement with the available data. Systematic discrepancies are found for lowlying S -wave states, in particular in the strong decays of $N(1535)$, $N(1650)$, $\Sigma(1750)$, $\Lambda^*(1405)$, $\Lambda(1670)$ and $\Lambda(1800)$.

Se discuten el espectro de masas y los decaimientos fuertes de las resonancias bariónicas de las familias N , Δ , Σ , Λ , Ξ y Ω en un modelo colectivo del nucleón. Se encuentra un buen ajuste con los datos experimentales. Hay una desviación sistemática para los estados en la onda parcial S , especialmente en los decaimientos fuertes de las resonancias $N(1535)$, $N(1650)$, $\Sigma(1750)$, $\Lambda^*(1405)$, $\Lambda(1670)$ y $\Lambda(1800)$.

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1 Introduction

The development of dedicated experimental facilities to probe the structure of hadrons in the nonperturbative region of QCD with far greater precision than before has stimulated us to reexamine hadron spectroscopy in a novel approach in which both internal (spin-flavor-color) and space degrees of freedom of hadrons are treated algebraically. The new ingredient is the introduction of a space symmetry or spectrum generating algebra for the radial excitations which for baryons was taken as $U(7)$ [1, 2, 3, 4]. The algebraic approach unifies the harmonic oscillator quark model with collective string-like models of baryons.

We present an analysis of the mass spectrum and strong couplings of both nonstrange and strange baryon resonances in the framework of a collective string-like qqq model in which the radial excitations are treated as rotations and vibrations of the strings. The algebraic structure of the model enables us to obtain transparent results (mass formula, selection rules and decay widths) that can be used to analyze and interpret the experimental data, and look for evidence for the existence of unconventional (*i.e.* non qqq) configurations of quarks and gluons, such as hybrid quark-gluon states $qqq-g$ or multiquark meson-baryon bound states $qqq-q\bar{q}$.

2 Mass spectrum

We consider baryons to be built of three constituent parts which are characterized by both internal and radial (or spatial) degrees of freedom. The internal degrees of freedom are described by the usual spin-flavor (sf) and color (c) algebras $SU_{\text{sf}}(6) \otimes SU_c(3)$. The radial degrees of freedom for the relative motion of the three constituent parts are taken as the Jacobi coordinates, which are treated algebraically in terms of the spectrum generating algebra of $U(7)$ [1]. The full algebraic structure is obtained by combining the radial part with the internal spin-flavor-color part

$$\mathcal{G} = U(7) \otimes SU_{\text{sf}}(6) \otimes SU_c(3) , \quad (1)$$

in such a way that the total baryon wave function is antisymmetric.

For the radial part we consider a collective (string-like) model of the nucleon in which the radially excited baryons are interpreted as rotations and vibrations of the string configuration of Fig. 1 [1]. The spectrum consists of a series of vibrational excitations labeled by (v_1, v_2) , and a tower of rotational excitations built on top of each vibration. The occurrence of linear Regge trajectories suggests to add, in addition to the vibrational frequencies κ_1 and κ_2 , a term linear in L . The slope of these trajectories is given by α . For the spin-flavor part of the mass operator we use a Gürsey-Radicati form [5]. These considerations lead to a mass formula for nonstrange and strange baryons of the form [4]

$$\begin{aligned} M^2 = & M_0^2 + \kappa_1 v_1 + \kappa_2 v_2 + \alpha L + a \left[\langle \hat{C}_2(SU_{\text{sf}}(6)) \rangle - 45 \right] \\ & + b \left[\langle \hat{C}_2(SU_{\text{f}}(3)) \rangle - 9 \right] + c \left[S(S+1) - \frac{3}{4} \right] \\ & + d \left[Y - 1 \right] + e \left[Y^2 - 1 \right] + f \left[I(I+1) - \frac{3}{4} \right] . \end{aligned} \quad (2)$$

The coefficient M_0^2 is determined by the nucleon mass $M_0^2 = 0.882 \text{ GeV}^2$. The remaining nine coefficients are obtained in a simultaneous fit to 48 three and four star resonances which have been assigned as octet and decuplet states. We find a good overall description of both positive and negative baryon resonances of the N , Δ , Σ , Λ , Ξ and Ω families with an r.m.s. deviation of $\delta = 33 \text{ MeV}$ [4] to be compared with $\delta = 39 \text{ MeV}$ in a previous fit to 25 N and Δ resonances [1]. Figures 2-5 show that there is no need for an additional energy shift for the positive parity states and another one for the negative parity states, as in the relativized quark model [6].

There are three states which show a deviation of about 100 MeV or more from the data: the $\Lambda^*(1405)$, $\Lambda^*(1520)$ and $\Lambda^*(2100)$ resonances are overpredicted by 236, 121 and 97 MeV, respectively. These three resonances are assigned as singlet states (and were not included in the fitting procedure). An additional energy shift for the singlet states (without effecting the masses of the octet and decuplet states) can be obtained by adding to the mass formula of Eq. (2) a term ΔM^2 that only acts on the singlet states. However, since $\Lambda^*(1405)$ and $\Lambda^*(1520)$ are spin-orbit partners, their mass splitting of 115 MeV cannot be reproduced by such a mechanism. In principle, this splitting can be obtained from a spin-orbit interaction, but the rest of the baryon spectra shows no evidence for such a large spin-orbit coupling.

A common feature to all q^3 quark models is the occurrence of missing resonances. In a recent three-channel analysis by the Zagreb group evidence was found for the existence of a P_{11} nucleon resonance at $1740 \pm 11 \text{ MeV}$ [7]. The first two P_{11} states at $1439 \pm 19 \text{ MeV}$ and $1729 \pm 16 \text{ MeV}$ correspond to the $N(1440)$ and $N(1710)$ resonances of the PDG [8]. It is tempting to assign the extra resonance as one of the missing resonances [9]. In the present calculation it is associated with the $^2 8_{1/2}[20, 1^+]$ configuration and appears at 1713 MeV, compared to 1880 MeV in the relativized quark model (RQM) [6] (see Table 1).

A recent analysis of new data on kaon photoproduction [10] has shown evidence for a D_{13} resonance at 1895 MeV [11]. In the present calculation, there are several possible assignments [4]. The lowest state that can be assigned to this new resonance is a vibrational excitation $(v_1, v_2) = (0, 1)$ with $^2 8_{3/2}[56, 1^-]$ at

1847 MeV. This state belongs to the same vibrational band as the $N(1710)$ resonance. In the relativized quark model a D_{13} state has been predicted at 1960 MeV [6].

3 Strong couplings

Decay processes are far more sensitive to details in the baryon wave functions than are masses. Here we consider the two-body strong decays of baryons by the emission of a pseudoscalar meson

$$B \rightarrow B' + M . \quad (3)$$

We use an elementary emission model in which the meson is emitted from a single constituent (see Fig. 6). The calculation of the strong decay widths involves a phase space factor, a spin-flavor matrix element which contains the dependence on the internal degrees of freedom and a spatial matrix element or form factor which in the collective model is obtained by folding with a distribution function of charge and magnetization [3, 4]. The transition operator that induces the strong decay is determined in a fit to the $N\pi$ and $\Delta\pi$ channels. It is important to stress that in the present analysis the transition operator is the same for *all* resonances and *all* decay channels. The calculations are carried out in the rest frame of the decaying resonance. For the pseudoscalar η mesons we introduce a mixing angle $\theta_P = -23^\circ$ between the octet and singlet mesons [8].

The calculated decay widths are to a large extent a consequence of spin-flavor symmetry and phase space. The spin-flavor symmetry gives rise to a selection rule that forbids the decays

$$\begin{aligned} N(^48[70, L^P]) &\rightarrow \Lambda(^28[56, 0^+]) + K , \\ \Lambda(^48[70, L^P]) &\rightarrow N(^28[56, 0^+]) + \overline{K} . \end{aligned} \quad (4)$$

This is analogous to the Moorhouse selection rule in electromagnetic couplings [12]. The use of the collective form factors introduces a power-law dependence on the meson momentum k , compared to, for example, an exponential dependence for harmonic oscillator form factors. Our results for the strong decay widths are in fair overall agreement with the available data, and show that the combination of a collective string-like qqq model of baryons and a simple elementary emission model for the decays can account for the main features of the data. As an example, in Table 2 we present the strong decays of three and four star Δ resonances.

There are a few exceptions which could indicate evidence for the importance of degrees of freedom outside the present qqq model of baryons.

3.1 Nucleon resonances

Nonstrange resonances decay predominantly into the π channel. Phase space factors suppress the η and K decays. Whereas the π decays are in fair agreement with the data, the η decays of octet baryons show an unusual pattern: the S -wave states $N(1535)$, $\Sigma(1750)$ and $\Lambda(1670)$ all are found experimentally to have a large branching ratio to the η channel, 74 ± 39 , 39 ± 28 and 9 ± 5 MeV, respectively [8], whereas the corresponding phase space factor is very small [13]. The small calculated η widths (< 0.5 MeV) for these resonances are due to a combination of spin-flavor symmetry and the size of the phase space factor. The results of our analysis suggest that the observed η widths are not due to a conventional qqq state, but may rather indicate evidence for the presence of a state in the same mass region of a more exotic nature, such as a pentaquark configuration $qqqq\bar{q}$ or a quasi-molecular S -wave resonance $qqq-q\bar{q}$ just below or above threshold, bound by Van der Waals type forces (for example $N\eta$, ΣK or ΛK [14]).

The K decays are suppressed with respect to the π decays because of phase space. In addition, the decay of the $N(1650)$, $N(1675)$ and $N(1700)$ resonances into ΛK is forbidden by the spin-flavor selection of Eq. (4). For $N(1675)$ and $N(1700)$ only an upper limit is known, whereas the $N(1650)$ resonance has

an observed width of 12 ± 7 MeV. However, this resonance is just above the ΛK threshold which may lead to a coupling to a quasi-bound meson-baryon S wave resonance.

3.2 Delta resonances

The strong decay widths of the Δ resonances are in very good agreement with the available experimental data. The same holds for the other resonances that have been assigned as decuplet baryons: $\Sigma^*(1385)$, $\Sigma^*(2030)$ and $\Xi^*(1530)$. For the decuplet baryons there is no S state around the threshold of the various decay channels, so therefore there cannot be any coupling to quasi-molecular configurations. Just as for the nucleon resonances, the η and K decays are suppressed relative to the π decays by phase space factors.

3.3 Sigma resonances

Strange resonances decay predominantly into the π and \overline{K} channel. Phase space factors suppress the η and K decays. The main discrepancy is found for $\Sigma(1750)$. In the discussion of nucleon resonances it was suggested that the S wave state $\Sigma(1750)$ is the octet partner of $N(1535)$. It has a large observed η width despite the fact that there is hardly any phase space available for this decay. This may indicate that it has a large quasi-molecular component.

3.4 Lambda resonances

Also for Λ resonances the η and K decays are suppressed with respect to the π and \overline{K} channels because of phase space factors. The strong decays of Λ resonances show more discrepancies with the data than the other families of resonances [4].

We have assigned $\Lambda(1670)$ as the octet partner of $N(1535)$ and $\Sigma(1750)$. Its decay properties into the η channel have already been discussed above. The calculated $N\overline{K}$ widths of $\Lambda(1800)$, $\Lambda(1830)$ and $\Lambda(2110)$ vanish because of the selection rule of Eq. (4), whereas all of them have been observed experimentally [8]. The $\Lambda(1800)S_{01}$ state has large decay width into $N\overline{K}^*(892)$. Since the mass of the resonance is just around the threshold of this channel, this could indicate a coupling with a quasi-molecular S wave. The $N\overline{K}$ width of $\Lambda(1830)$ is relatively small (6 ± 3 MeV), and hence in qualitative agreement with the selection rule. The situation for the $\Lambda(2110)$ resonance is unclear.

The $\Lambda^*(1405)$ resonance has a anomalously large decay width (50 ± 2 MeV) into $\Sigma\pi$. This feature emphasizes the quasi-molecular nature of $\Lambda^*(1405)S_{01}$ due to the proximity of the $N\overline{K}$ threshold. It has been shown [15] that the inclusion of the coupling to the $N\overline{K}$ and $\Sigma\pi$ decay channels produces a downward shift of the qqq state toward or even below the $N\overline{K}$ threshold. In a chiral meson-baryon Lagrangian approach with an effective coupled-channel potential the $\Lambda^*(1405)$ resonance emerges as a quasi-bound state of $N\overline{K}$ [14].

4 Summary and conclusions

In this contribution we have presented a systematic analysis of the masses and the strong couplings of baryon resonances in a collective string-like qqq model of the nucleon. The algebraic structure of the model, both for the internal degrees of freedom of spin-flavor-color and for the spatial degrees of freedom, gives rise to transparent results, such as a mass formula, selection rules and closed expressions for decay widths.

Whereas the mass spectrum is reasonably well described, the strong decay widths are only qualitatively described. The combination of a collective string-like qqq model of baryons and a simple elementary emission model for the decays can account for the main features of the data. The main discrepancies are

found for the low-lying S -wave states, specifically $N(1535)$, $N(1650)$, $\Sigma(1750)$, $\Lambda^*(1405)$, $\Lambda(1670)$ and $\Lambda(1800)$. All of these resonances have masses which are close to the threshold of a meson-baryon decay channel, and hence they could mix with a quasi-molecular S wave resonance of the form $qqq - q\bar{q}$. In contrary, in the spectrum of decuplet baryons there are no low-lying S states with masses close to the threshold of a particular decay channel, and their spectroscopy is described very well.

The results of this analysis suggest that in future experiments particular attention be paid to the resonances mentioned above in order to elucidate their structure, and to look for evidence of the existence of exotic (non qqq) configurations of quarks and gluons.

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References

- [1] R. Bijker, F. Iachello and A. Leviatan, Ann. Phys. (N.Y.) **236** (1994), 69.
- [2] R. Bijker, F. Iachello and A. Leviatan, Phys. Rev. C **54** (1996), 1935.
- [3] R. Bijker, F. Iachello and A. Leviatan, Phys. Rev. D **55** (1997), 2862.
- [4] R. Bijker, F. Iachello and A. Leviatan, Ann. Phys. (N.Y.) **284** (2000), 89.
- [5] F. Gürsey and L.A. Radicati, Phys. Rev. Lett. **13** (1964), 173.
- [6] S. Capstick and N. Isgur, Phys. Rev. D **34** (1986), 2809.
- [7] M. Batinić, I. Dadić, I. Šlaus, A. Švarc, B.M.K. Nefkens and T.-S.H. Lee, Phys. Scr. **58** (1998), 15.
- [8] Particle Data Group, Eur. Phys. J. C **15** (2000), 1.
- [9] S. Capstick, T.-S.H. Lee, W. Roberts and A. Švarc, Phys. Rev. C **59** (1999), R3002.
- [10] M.Q. Tran et al., Phys. Lett. B **445** (1998), 20.
- [11] T. Mart and C. Bennhold, Phys. Rev. C **61** (2000), 012201.
- [12] R.G. Moorhouse, Phys. Rev. Lett. **16** (1966), 772.
- [13] B.M.K. Nefkens, in ‘Proceedings of the Fourth CEBAF/INT Workshop: N^* Physics’, Eds. T.-S.H. Lee and W. Roberts, World Scientific, Singapore, 1997, p. 186.
- [14] N. Kaiser, T. Waas and W. Weise, Nucl. Phys. A **612** (1997), 297.
- [15] M. Arima, S. Matsui and K. Shimizu, Phys. Rev. C **49** (1994), 2831.

Table 1: Masses of the first three P_{11} states in MeV

PDG [8]	Zagreb [7]	RQM [9]	present [4]
$N(1440)$	1439 ± 19	1540	1444
$N(1710)$	1729 ± 16	1770	1683
	1740 ± 11	1880	1713

Table 2: Strong decay widths of three and four star delta resonances in MeV. The experimental values are taken from [8]. Decay channels labeled by – are below threshold.

Baryon	$N\pi$	ΣK	$\Delta\pi$	$\Delta\eta$	$\Sigma^* K$
$\Delta(1232)P_{33}$	116 119 ± 5	–	–	–	–
$\Delta(1600)P_{33}$	108 61 ± 32	–	25 193 ± 76	–	–
$\Delta(1620)S_{31}$	16 38 ± 11	–	89 68 ± 26	–	–
$\Delta(1700)D_{33}$	27 45 ± 21	0	144 135 ± 64	–	–
$\Delta(1905)F_{35}$	9 36 ± 20	1	45 $< 45 \pm 45$	1	0
$\Delta(1910)P_{31}$	42 52 ± 19	2	4	0	0
$\Delta(1920)P_{33}$	22 28 ± 19	1	29	1	0
$\Delta(1930)D_{35}$	0 53 ± 23	0	0	0	0
$\Delta(1950)F_{37}$	45 120 ± 14	6	36 80 ± 18	2	0
$\Delta(2420)H_{3,11}$	12 40 ± 22	4	11	2	1

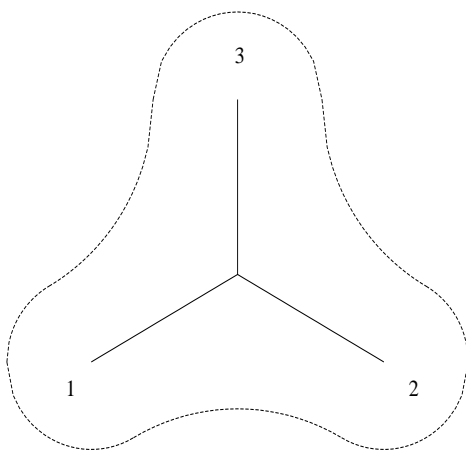


Figure 1: Collective model of baryons.

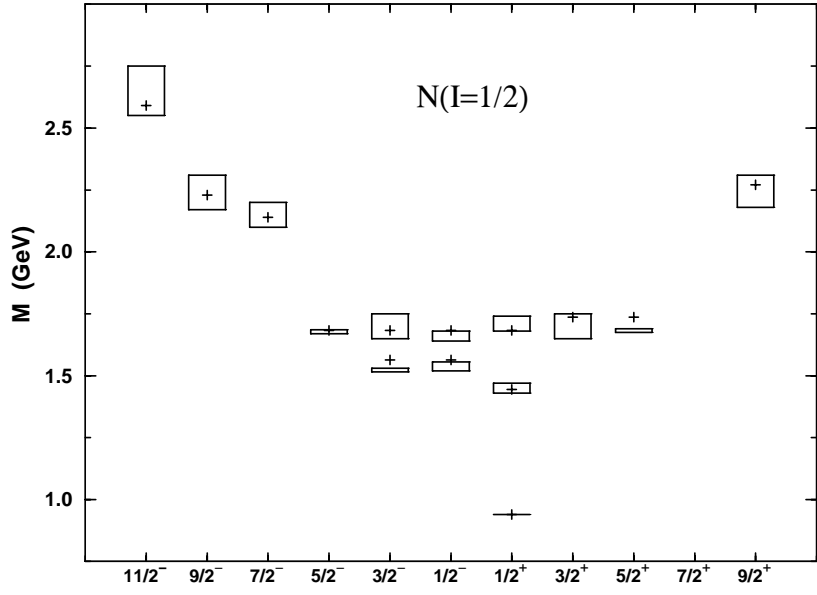


Figure 2: Comparison between the experimental mass spectrum of three and four star nucleon resonances (boxes) and the calculated masses (+). The experimental values are taken from [8].

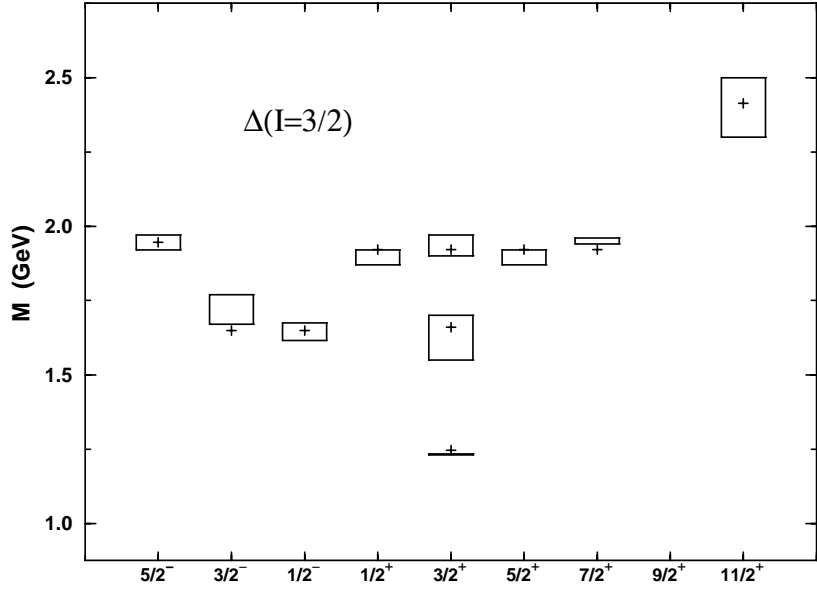


Figure 3: As Fig. 2, but for Δ resonances.

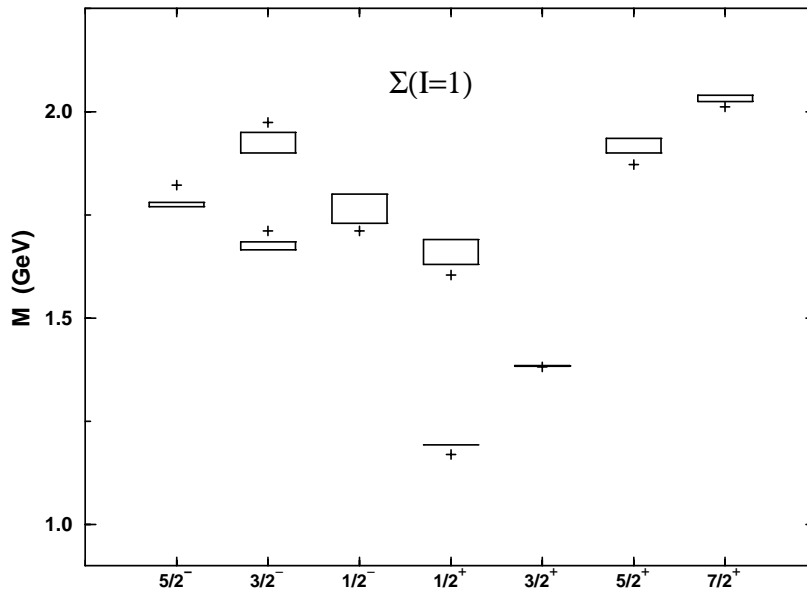


Figure 4: As Fig. 2, but for Σ resonances.

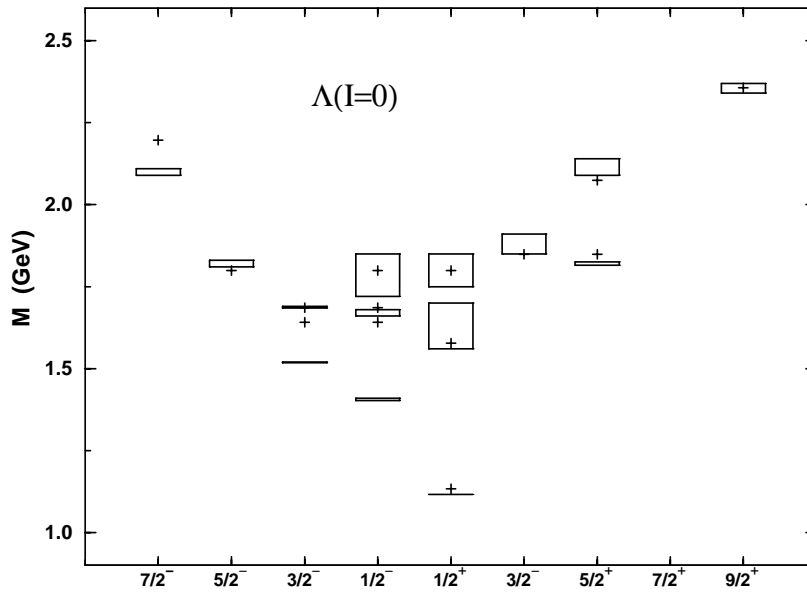


Figure 5: As Fig. 2, but for Λ resonances.

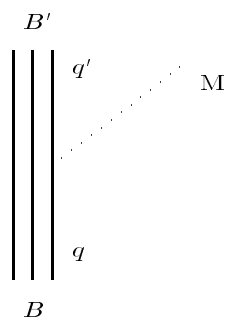


Figure 6: Elementary meson emission